

Dark Matter & Dark Energy

In Cosmology

Texas XXI

Rocky Kolb
Fermilab & Univ. of Chicago
December 13, 2002

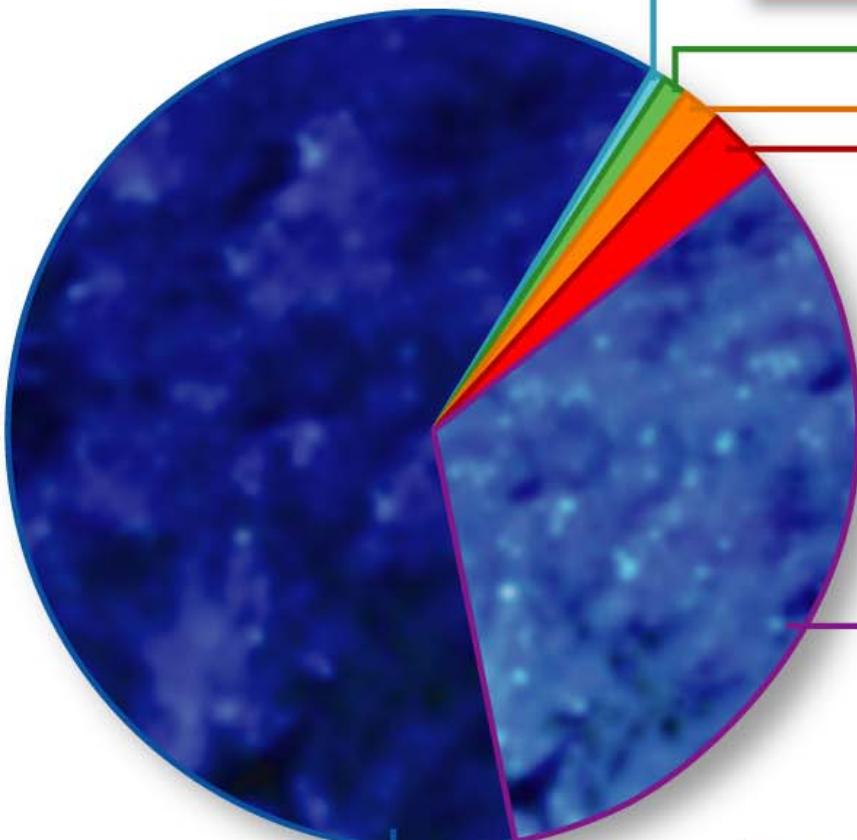
viale

dell'Astronomia

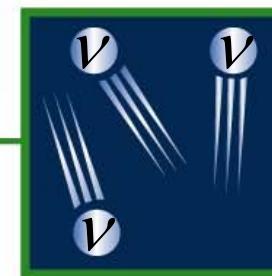
via

della Fisica

Torta Cosmica



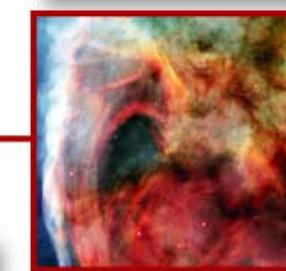
Heavy Elements:
0.03%



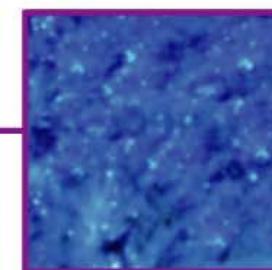
Neutrinos:
0.47%



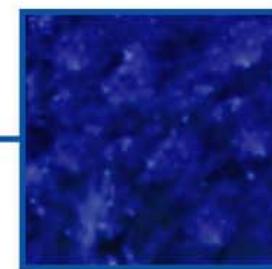
Stars:
0.5%



Free H
and He
4%



Dark Matter:
25%



Dark Energy:
70%

Cosmological constant

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

1917 Einstein proposes cosmological constant

1929 Hubble discovers expansion of the universe

1934 Einstein calls it “my biggest blunder”

1998 Astronomers find evidence for it



Cosmological constant

Mass density of space:

$$\rho_\Lambda \simeq 10^{-30} \text{ g cm}^{-3} \simeq (10^{-4} \text{ eV})^4 = (10^{-3} \text{ cm})^{-4}$$
$$\Lambda = 8\pi G \rho_\Lambda = (10^{29} \text{ cm})^{-2} = (10^{-33} \text{ eV})^2$$

The unbearable lightness of nothing!

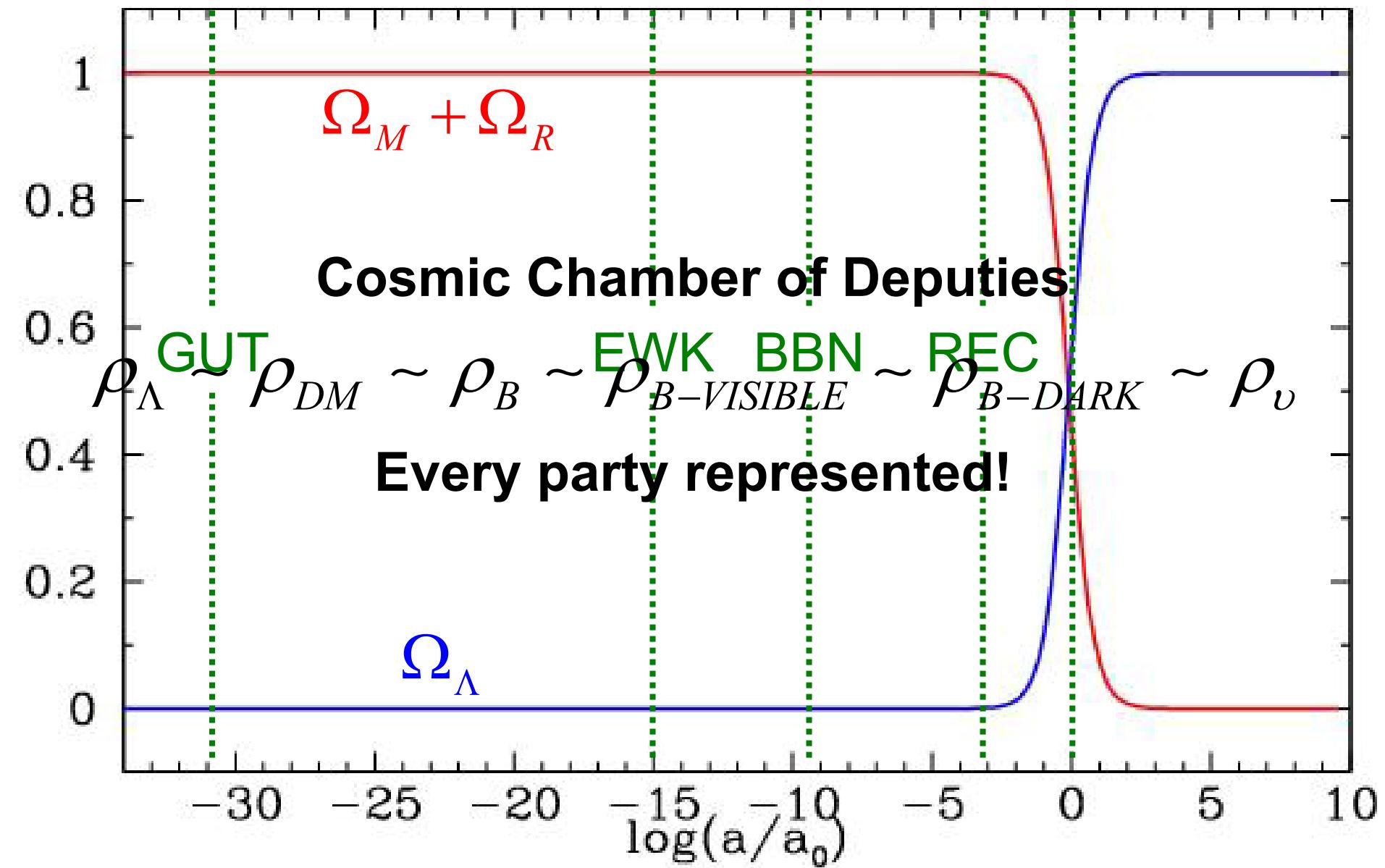
Cosmo-illogical constant?

Numerology:

$$\rho_V = \exp(-2/\alpha) \quad \rho_V = M_{\text{SUSY}}^8 / M_{Pl}^4$$

$$m_\nu = 10^{-3} \text{ eV} \quad R_5 = 10^{-4} \text{ cm}$$

Cosmic coincidence



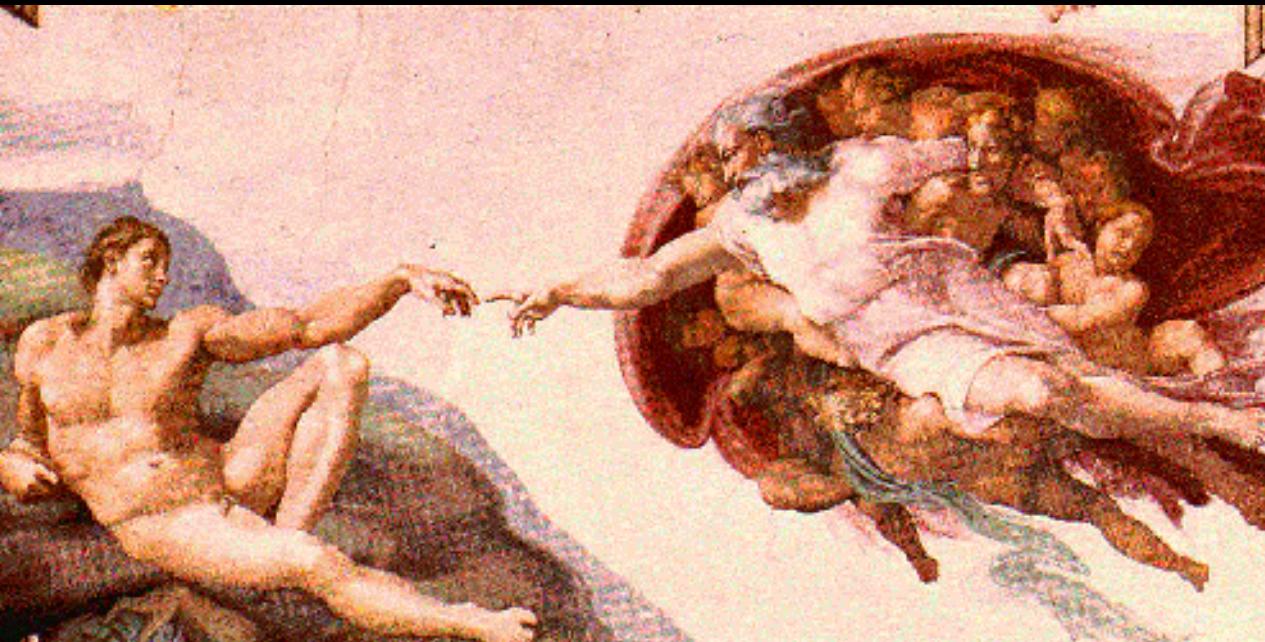
Λ : the uninvited guest

1. No unbroken symmetry demands $\Lambda=0$
2. Nothing sets the scale
3. Scale seems unrelated to any other energy scale
 - . . . seems to require $m \sim 10^{-33}$ eV
 - . . . fifth-force experiments?

Non l'avrei giammai creduto;
Ma farò quel che potrò.

*Mozart/Da Ponte,
Don Giovanni, Act II*

4. *Deal with it!*



Top down
(string inspired)



Bottom up
**(phenomenology
perspired)**

Dealing with Λ

1. Alcohol*
2. Drugs*
3. Anthropic principle*
4. Invent dynamics

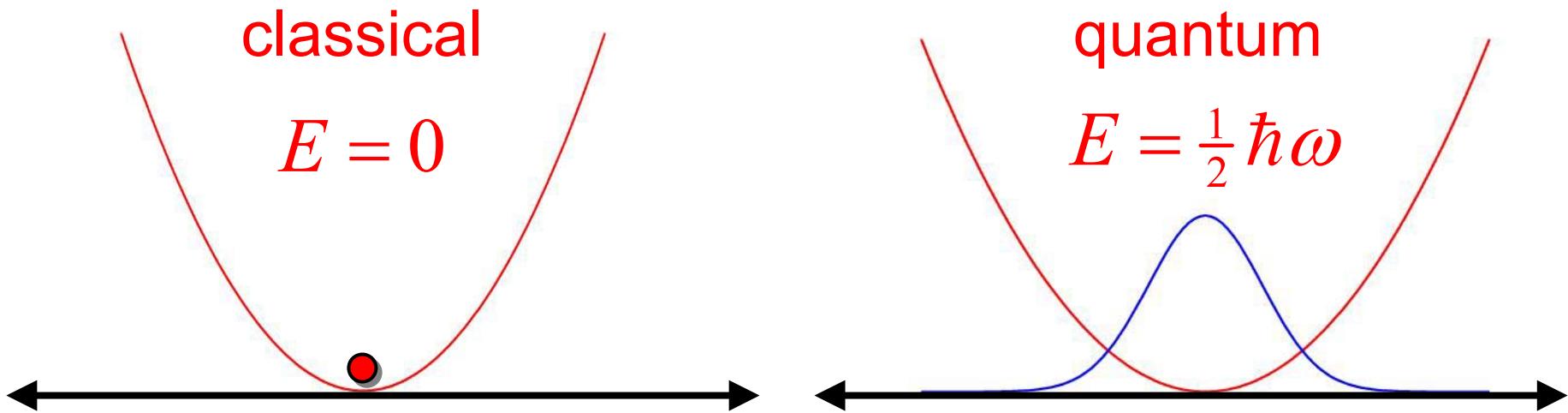
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

5. Other contributions!

* Therapy, medication, and twelve-step programs available.

Quantum uncertainty

Fourier modes of all fields are harmonic oscillators with a zero-point energy



$$\rho = \sum_{all\ particles} \pm \int d^3k \sqrt{k^2 + m^2}$$

Quantum uncertainty

$$\rho = \sum_{\text{all particles}} \pm \int d^3k \sqrt{k^2 + m^2} \simeq \sum_{\text{all particles}} \pm \int_{-\Lambda_C}^{\Lambda_C} d^3k \ k^4$$

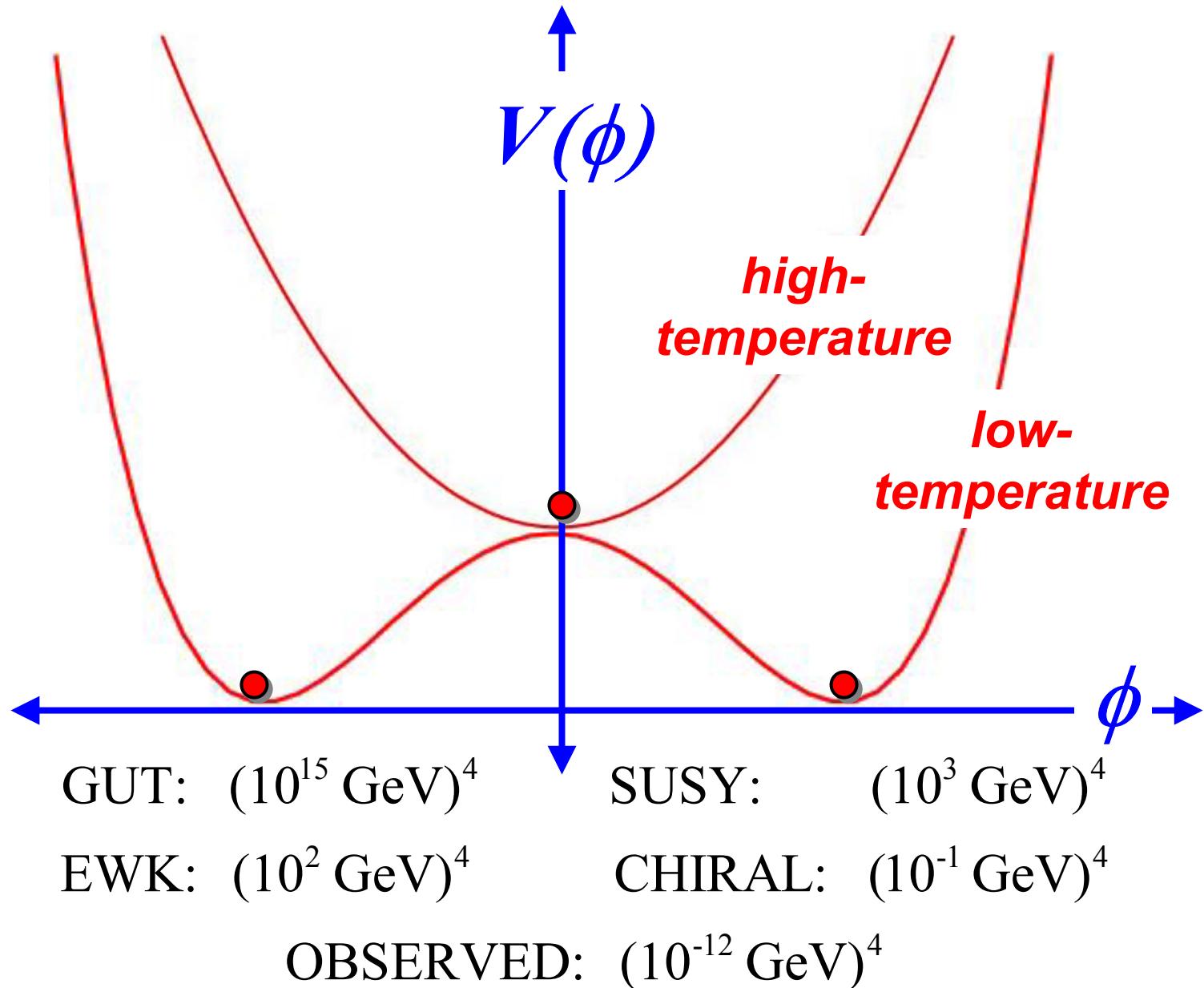
$$\Lambda_C = \infty : \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

$$\Lambda_C = M_{Pl} : \quad \rho_\Lambda = M_{Pl}^4 = (10^{28} \text{ eV})^4$$

$$\Lambda_C = M_{SUSY} : \quad \rho_\Lambda = M_{SUSY}^4 = (10^{12} \text{ eV})^4$$

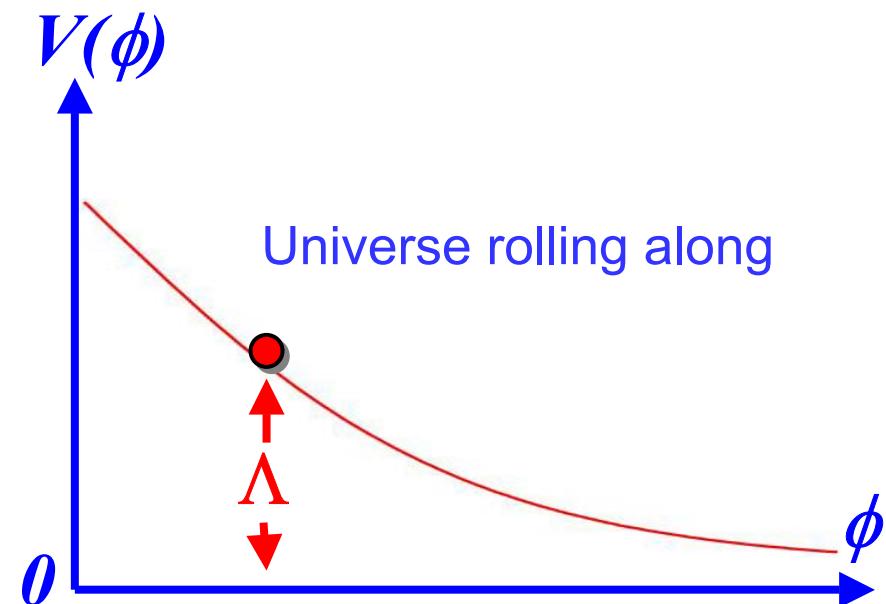
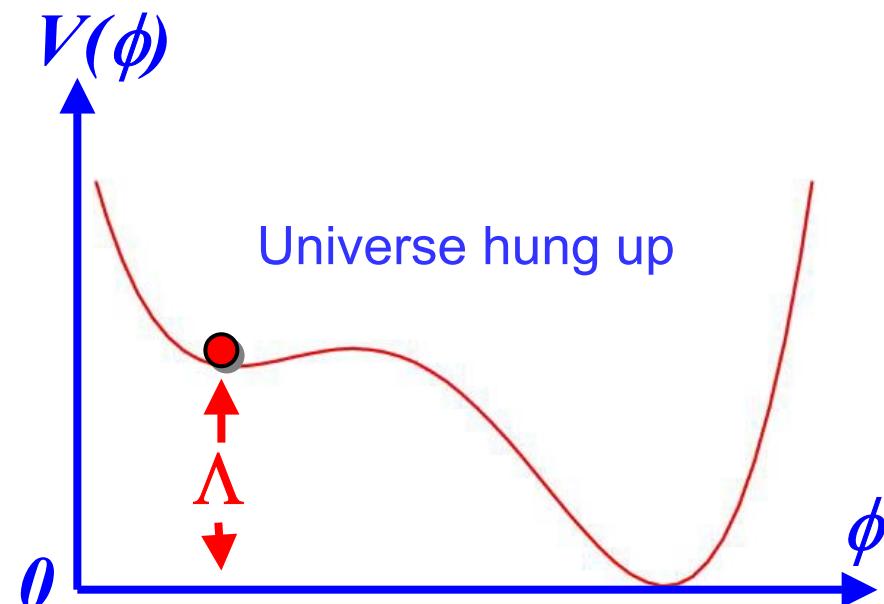
$$\Lambda_C = 10^{-3} \text{ eV} : \quad \rho_\Lambda = \text{Observed}$$

Spontaneous symmetry breaking



Balancing other contributions

- Many possible contributions.
- Why then is total so small?
- Perhaps unknown dynamics sets global vacuum energy equal to zero.....*but we're not there yet!*



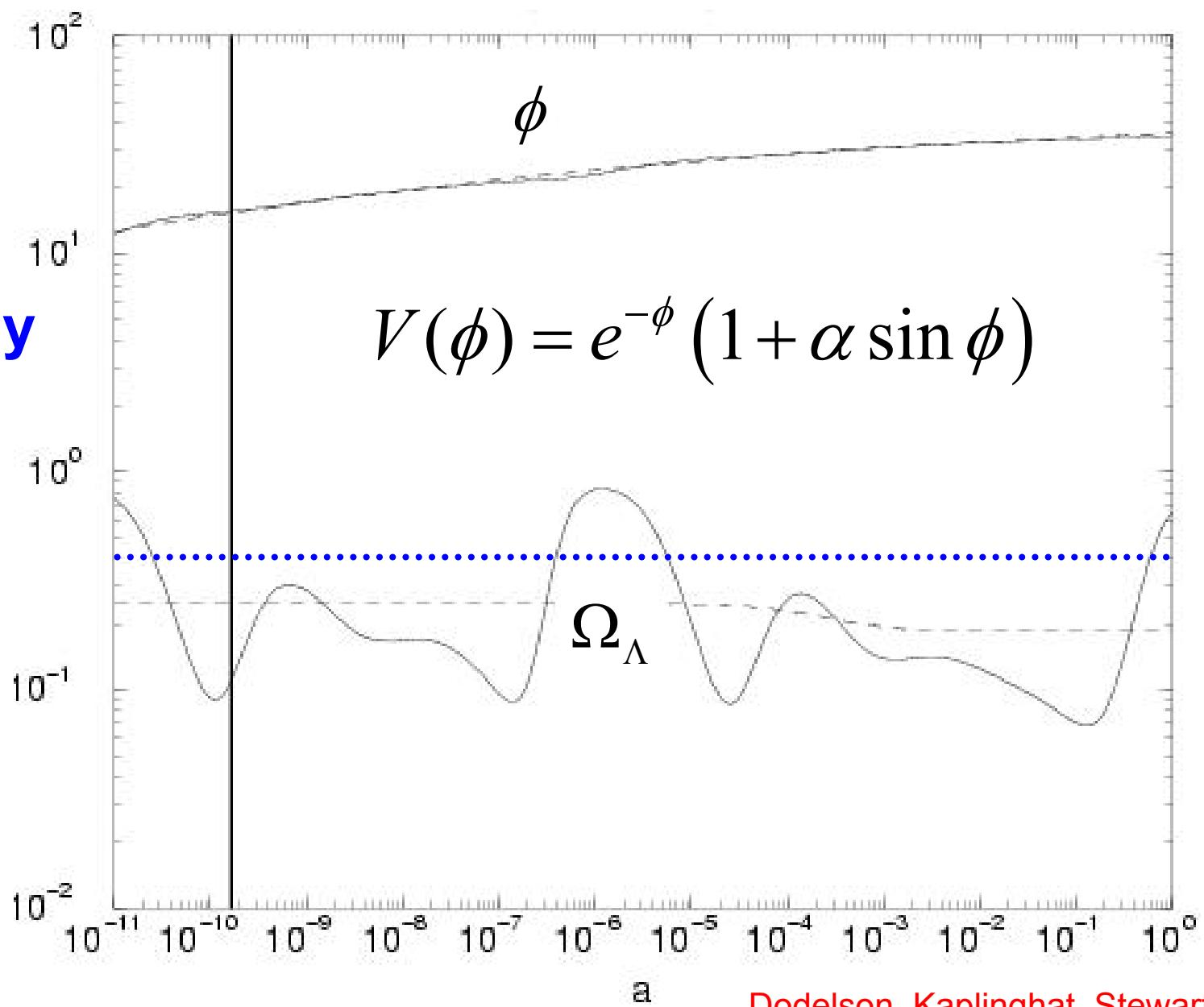
Balancing other contributions

- But *why now?*
- Tracker potentials, $e^{-\phi}$, ϕ^{-n} , ... relate dark energy to other contributions.*
- *Why now?..... “close to matter domination”*
- *Why now?..... “it’s just that time”*

* Wetterich; Ratra & Peebles; Steinhardt;

Punctuated vacuum domination

**dark energy
≠ destiny**

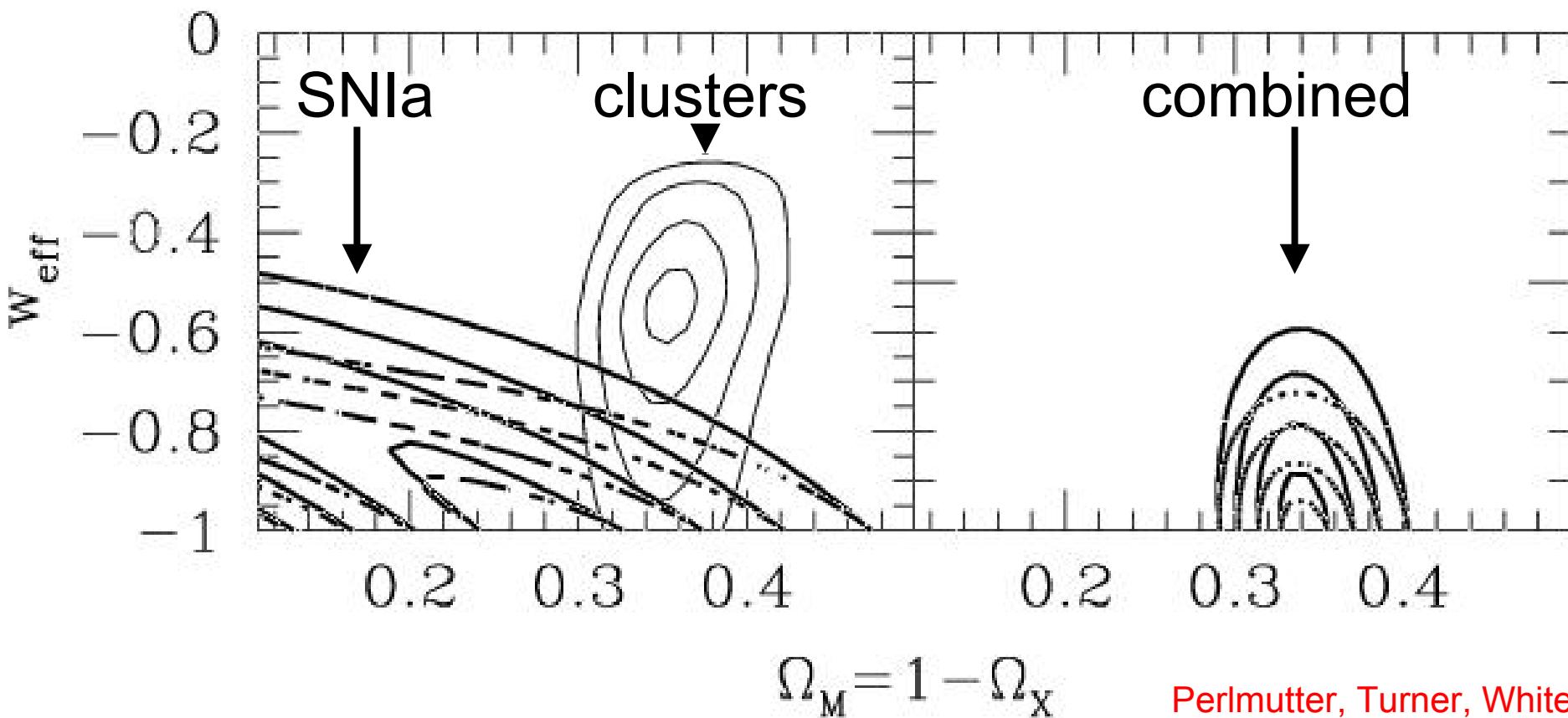


For now...parameterize

$$w = p_V / \rho_V$$

$w = -1$ for constant Λ

$-1 < w \leq -1/3$ for dynamical dark energy



$$\Omega_M = 1 - \Omega_X$$

Perlmutter, Turner, White

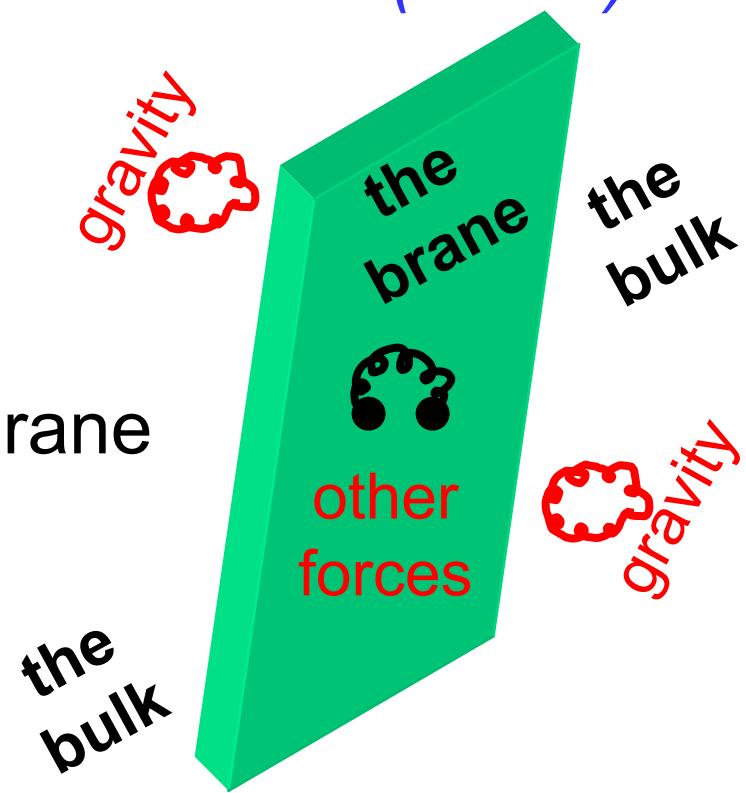
Aether of the 21st century?

- It's an infrared issue!
- Scalars (quintessence, trackers,)?
- Tensors (gravity at large distances)?

Brane cosmology

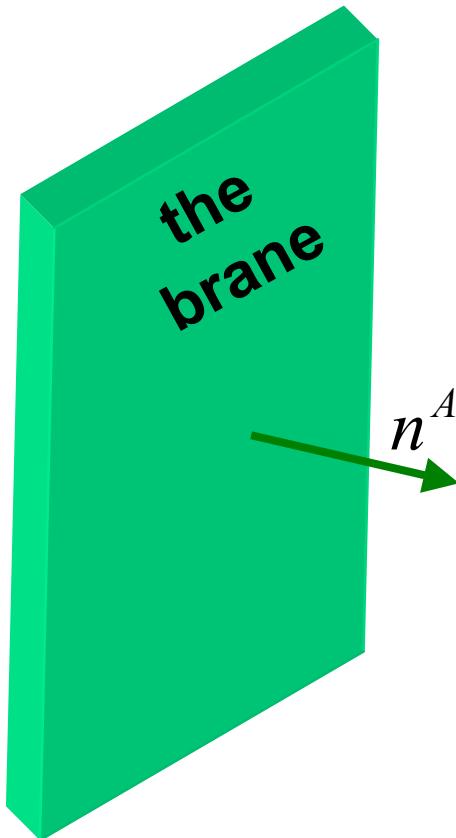
Extra dimensions required in string theory/M-theory

- Extra dimensions small and compact (Kaluza-Klein)
 - or -
- Matter confined to a $(3+1)$ -dimensional slice (*brane*) in a $(3+1+n)$ -dimensional *bulk*.
 - Gravity lives in the bulk
(closed strings)
 - Other forces confined to the brane
(open strings)



Brane cosmology

- Israel junction condition (Israel 1966)



- n^A : unit vector normal to the brane
- $h_{AB} = g_{AB} - n_A n_B$: the induced metric
- $\kappa_{AB} = h_A^C \nabla_C n_B$: the extrinsic curvature

$$[\kappa_{\mu\nu}] = -M_*^{-3} T_{\mu\nu}^{BRANE}$$

[....] = discontinuity across the brane

$$a'' = \langle a'' \rangle + [a'] \delta(y)$$

discontinuity in second derivative of scale factor

Braneless cosmology

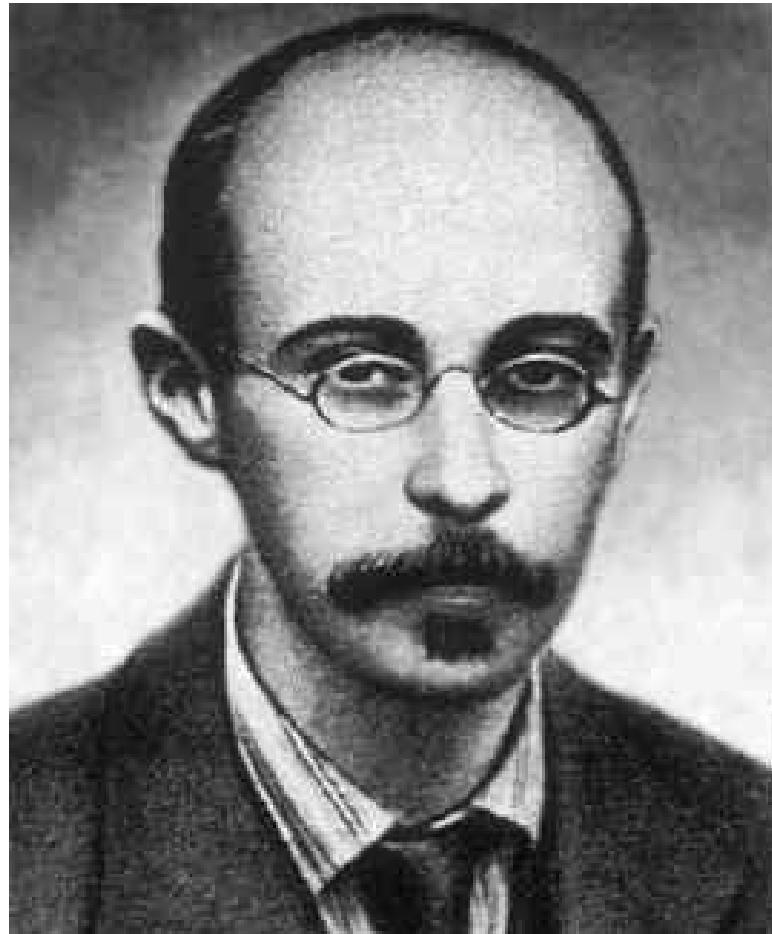
- Old Friedmann law

$$G_{00} = 8\pi G_N T_{00}$$

$$3H^2 = \frac{8\pi}{M_{Pl}^2} \rho$$

**SNIa evidence
for dark energy:**

$$\int \frac{dz}{H(z)}$$



Friedmann (1921)

Brane cosmology

- New Friedmann law Binetruy, Deffayet, Langlois (2000)

$$H^2 = \frac{\Lambda}{6} + \frac{M_*^{-6}}{36} \rho^2 + \frac{c}{a^4(t, y=0)}$$

- Possible solution Randall & Sundrum (2000)

Introduce a tension σ on the brane $\rho \rightarrow \rho + \sigma$

$$H^2 = \left(\frac{\Lambda}{6} + \frac{M_*^{-6}}{36} \sigma^2 \right) + \frac{M_*^{-6}}{18} \sigma \rho + \frac{M_*^{-6}}{36} \rho^2 + \frac{c}{a^4(t, y=0)}$$

cosmological constant (cancels?) $\frac{M_*^{-6}}{18} \sigma = \frac{8\pi G}{3}$ unconventional corrections
Friedmann equation

Brane cosmology

- Friedmann equation modified today

$$H^2 = A\rho \left[1 + \left(\rho / \rho_{\text{cutoff}} \right)^{n-1} \right]$$

Freese & Lewis

- Gravitational force law modified at large distance

Five-dimensional at cosmic distances

Deffayet, Dvali & Gabadadze

- Tired gravitons

Gravitons metastable - leak into bulk

Gregory, Rubakov & Sibiryakov
Dvali, Gabadadze & Porrati

- Gravity repulsive at cosmological distance

$R \sim \text{Gpc}$

Csaki, Erlich, Hollowood & Terning

- $n=1$ KK graviton mode very light

$$m \sim (\text{Gpc})^{-1}$$

Kogan, Mouslopoulos, Papazoglou, Ross & Santiago

- 3+1 Lorentz invariance broken

In the IR!

Chung, Kolb & Riotto

Dark matter



Nonbaryonic dark matter

Familiar candidate: a neutralino

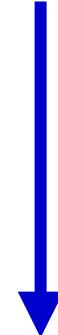
“a simple, elegant, compelling explanation for a complex physical phenomenon”

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- *Tommy Gold*

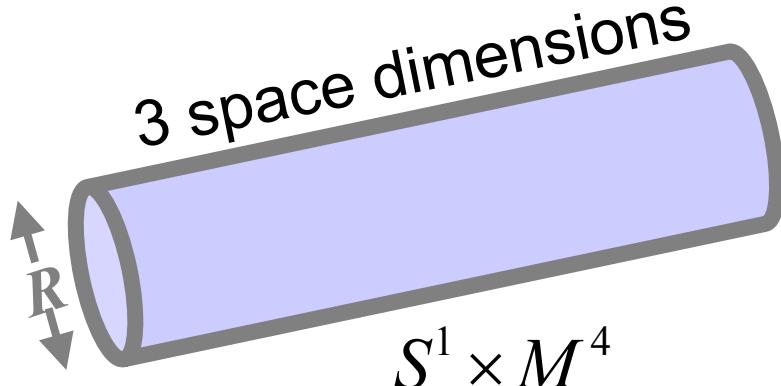
Particle Dark Matter Candidates

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, ...) (cold dark matter)
- axions, axion clusters
- LKP (lightest Kaluza-Klein particle)



Kaluza-Klein Particles

Kolb & Slansky (84); Servant & Tait (02); Cheng, Feng & Matchev (02)



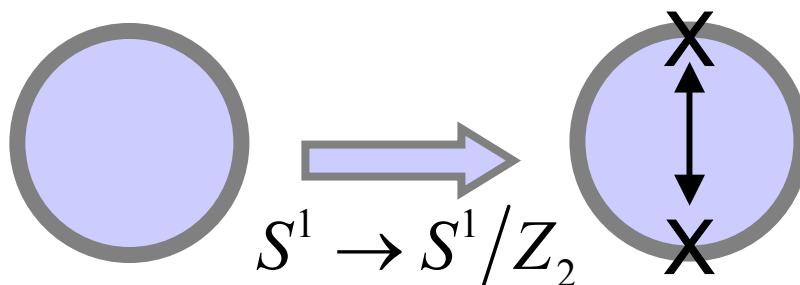
Quantized Kaluza-Klein excitations

$$\begin{aligned} E^2 &= \vec{p}^2 + p_5^2 & p_5^2 &= n^2 / R^2 \\ &= \vec{p}^2 + M_n^2 & M_n^2 &= n^2 / R^2 \end{aligned}$$

Conservation of momentum \rightarrow conservation of KK mode number

First excited mode ($n=1$) stable, mass R^{-1}

need
chiral
fermions

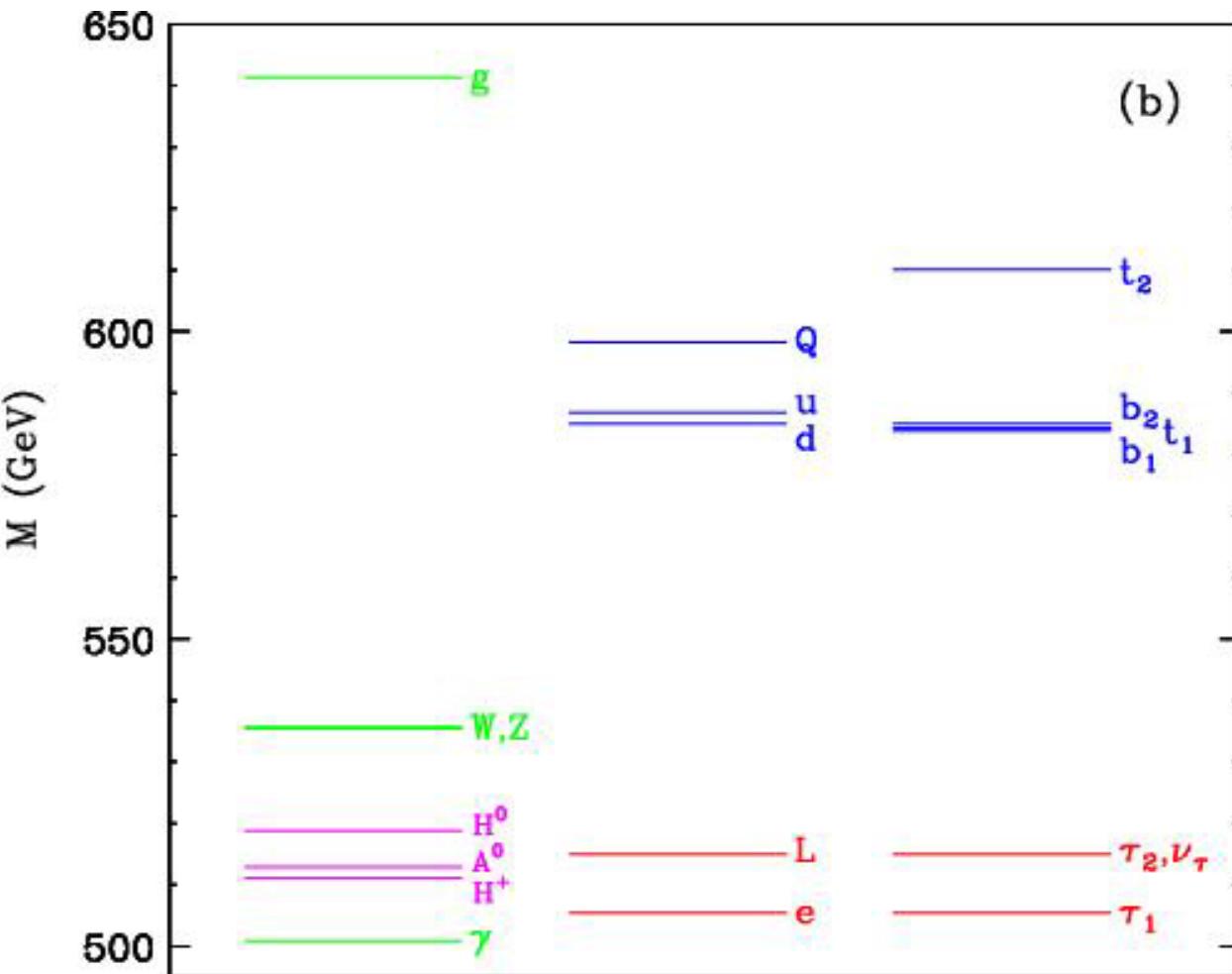


KK quantum number
 \longrightarrow KK parity

First excited mode ($n=1$) stable, mass R^{-1}

Kaluza-Klein Particles

$$R^{-1} = 500 \text{ GeV}$$



- Looks like SUSY
Cheng, Matchev & Schmaltz
- LKP = KK photon
Cheng, Matchev & Schmaltz
- Beware KK graviton
Kolb, Servant & Tait
- Direct detection
Servant & Tait
Cheng, Feng & Matchev
- Indirect detection
Bertrone, Servant, Sigl

Particle Dark Matter Candidates

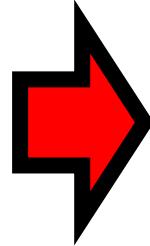
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- solitons (B-balls; Q-balls; Odd-balls, Screw-balls....)



Balls

- **Q-balls (non-topological solitons):** S. Coleman; T.D. Lee

Scalar field with
conserved global
charge “Q”



Ground state is a
Q-ball, lump of coherent
scalar condensate

$$E \propto Q^{3/4} : \text{can't decay to Q free particles}$$

- **Q-ball production and evolution:**

Solitogenesis

Frieman, Gelmini, Gleiser & Kolb

Solitosynthesis

Frieman, Olinto, Gleiser & Alcock; Greist & Kolb

Statistical fluctuations

Greist, Kolb & Masssarotti

Condensate fragmentation

Kusenko & Shaposhnikov

Balls

- Q-balls exist in MSSM
scalars = squarks & sleptons

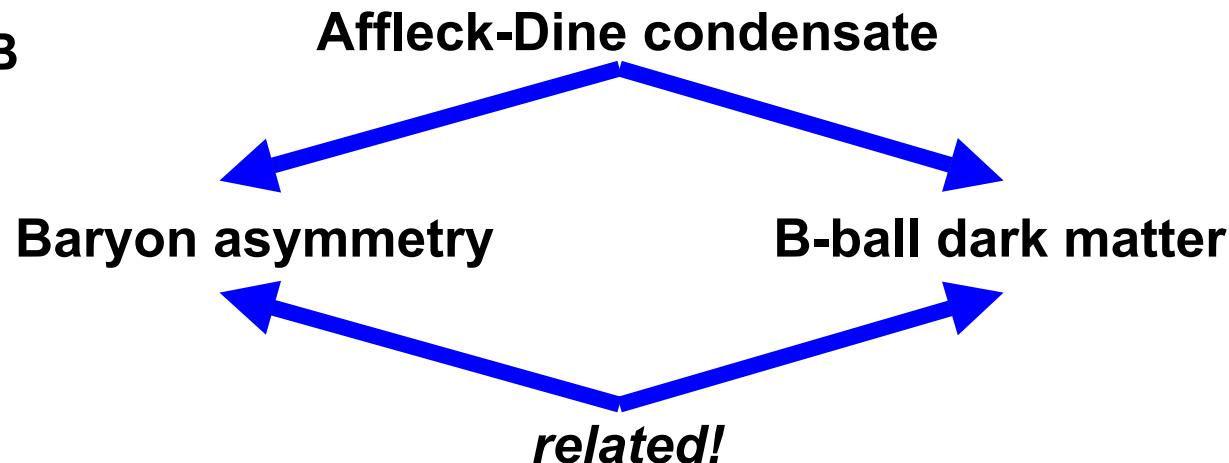
Kusenko, Shapashnikov & Tinyakov

$$M_B \sim (1 \text{ TeV}) \times B^{3/4} \quad (\text{stable for } B \geq 10^{12})$$

- Fragmentation of
Affleck-Dine condensate

$$M_B \sim 10^{-3} \text{ g} \quad (B \simeq 10^{24})$$

- Relates Ω_{DM} to Ω_B

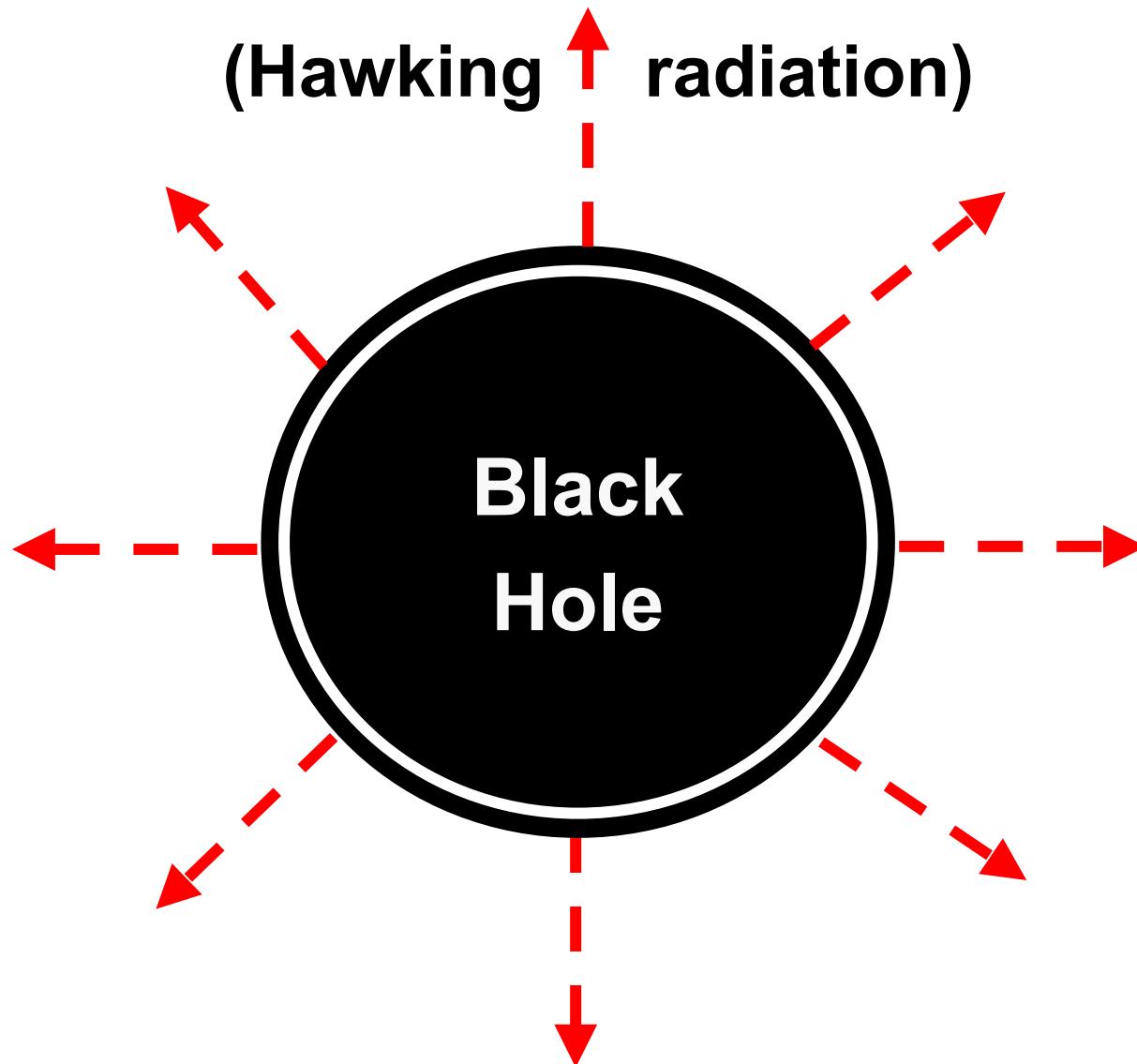


Particle Dark Matter Candidates

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 - WIMPZILLAS
 -
 -
 -
- 

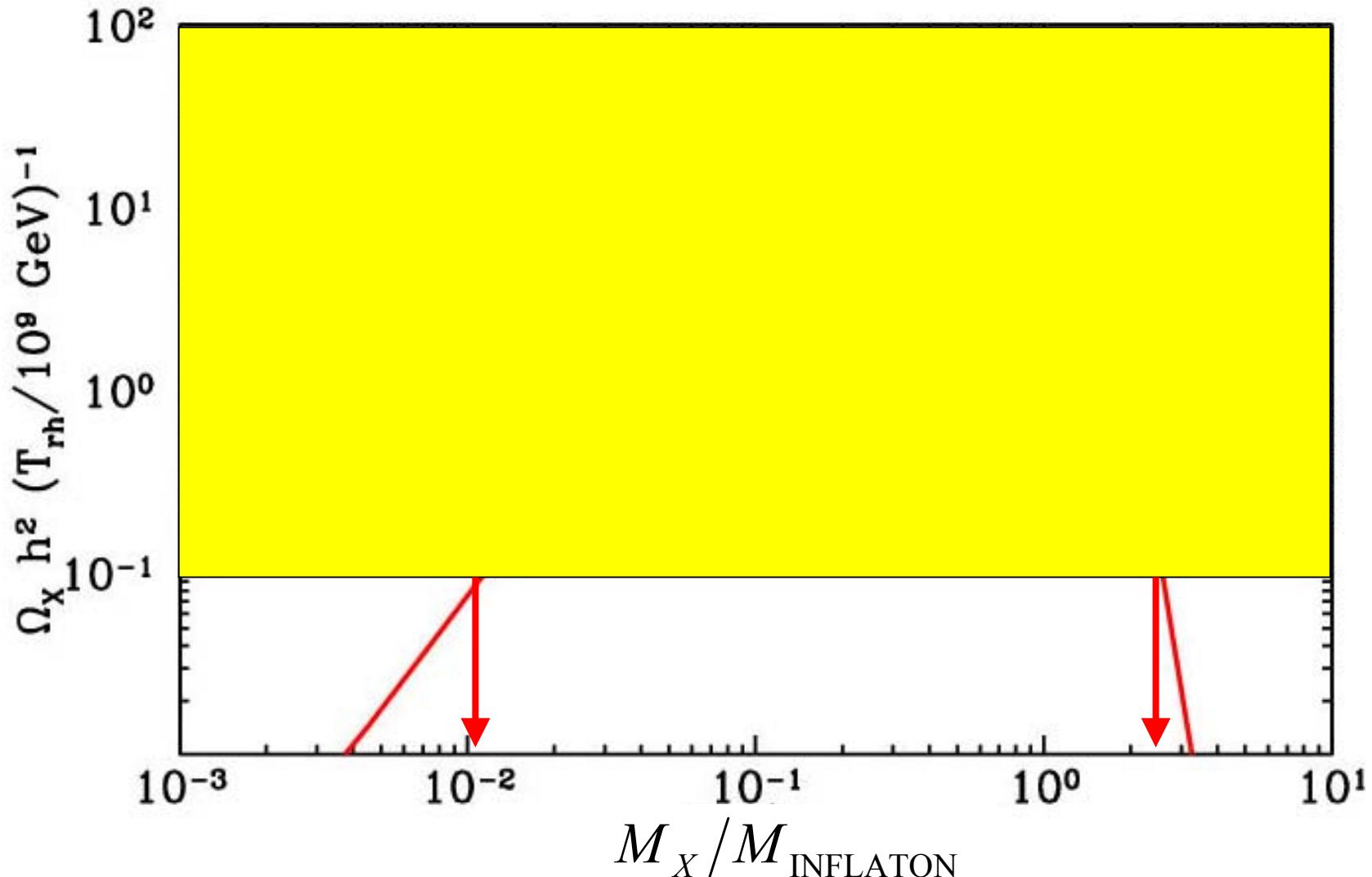
Disturbing the vacuum

Strong gravitational field → particle production



Particle production

Chung, Kolb& Riotto; Kuzmin & Tkachev)



$\Omega_X \approx 1$ for $M_X/M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV}$

Wimpzilla characteristics:

- supermassive: ($\sim 10^{12}$ GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
 - sterile?
 - electrically charged?
 - strong interactions?
 - weak interactions?
- unstable (lifetime > age of the universe)?

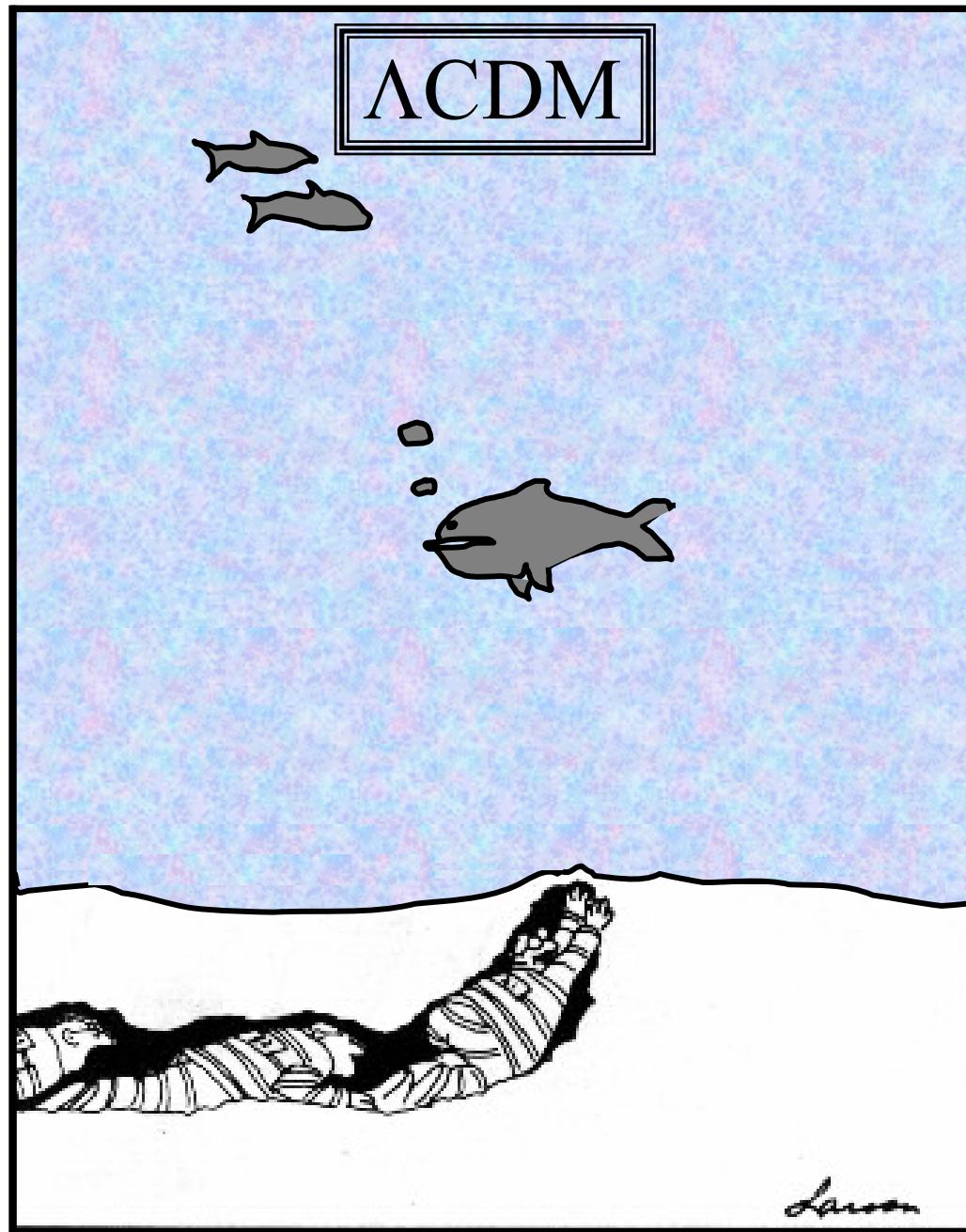
Dark matter

WIMP

or

WIMPZILLA





We're almost free, I just felt the first drops of rain

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<http://home.fnal.gov/~rocky/firenze.pdf>